Towards Ponderomotive Squeezing

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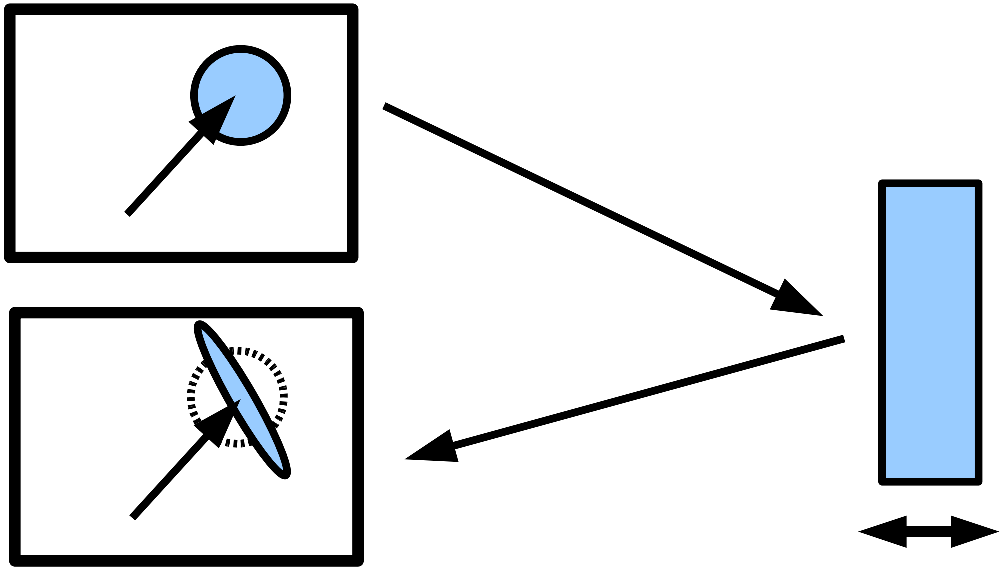
Outline

- 8:30 AM talk – 0 equations and lots of pictures
- Goals of experiments
  - Explore radiation pressure effects
    - Ponderomotive squeezing
    - Optical spring / parametric instability
- Path to goals
  - Phase I experiment – completed!
    - Get our feet wet. See something.
  - Phase II experiment – almost completed!
    - Test dynamics in single cavity.
  - Phase III – ongoing.
    - Measure ponderomotive squeezing.

The principle

- Use radiation pressure as the squeezing mechanism
  - Intensity fluctuations of laser field create test mass motion
  - Test mass motion creates phase shift of reflected light
  - Phase shift is proportional to intensity fluctuations – this correlation gives the squeezing effect.

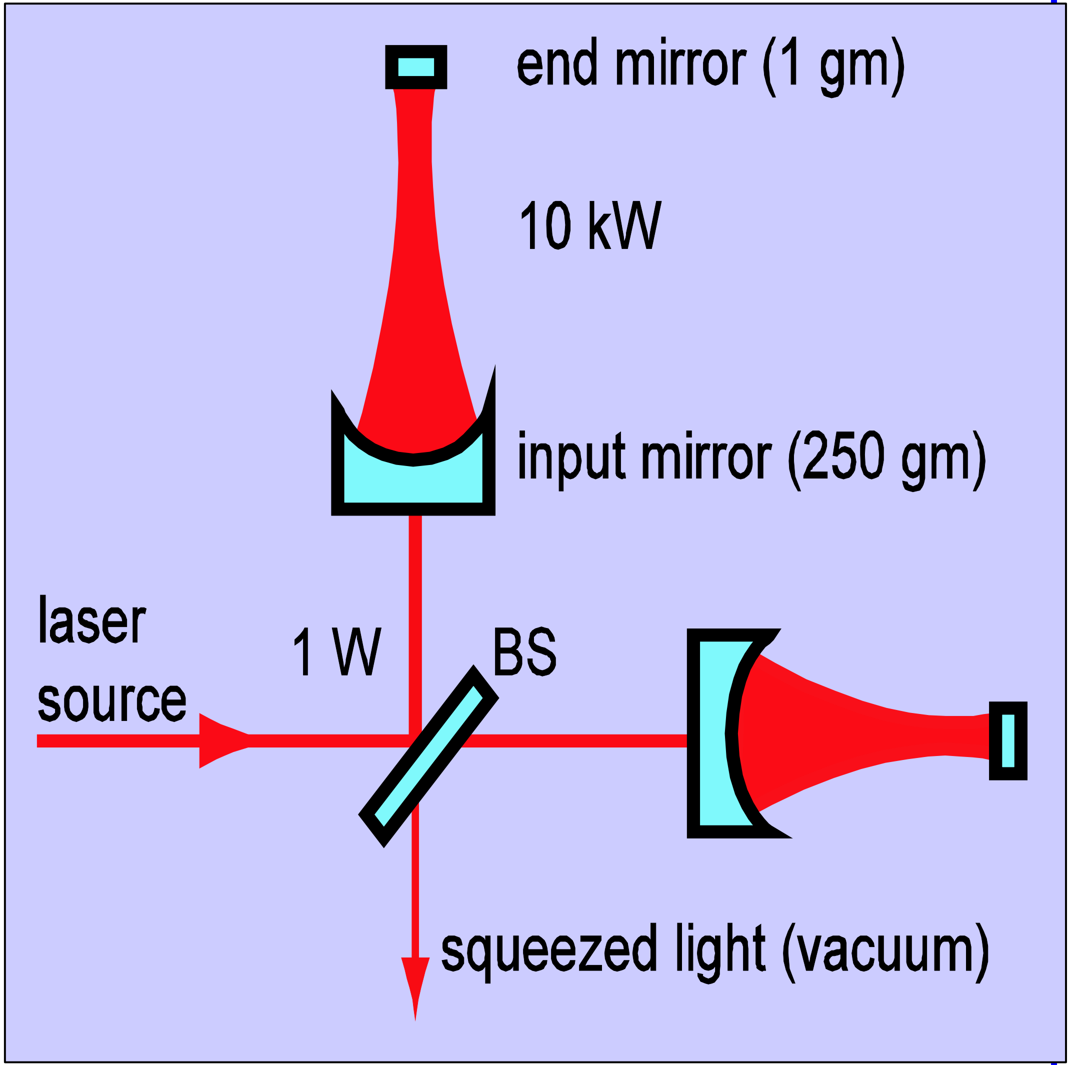
Field transformation



The ponderomotive interferometer

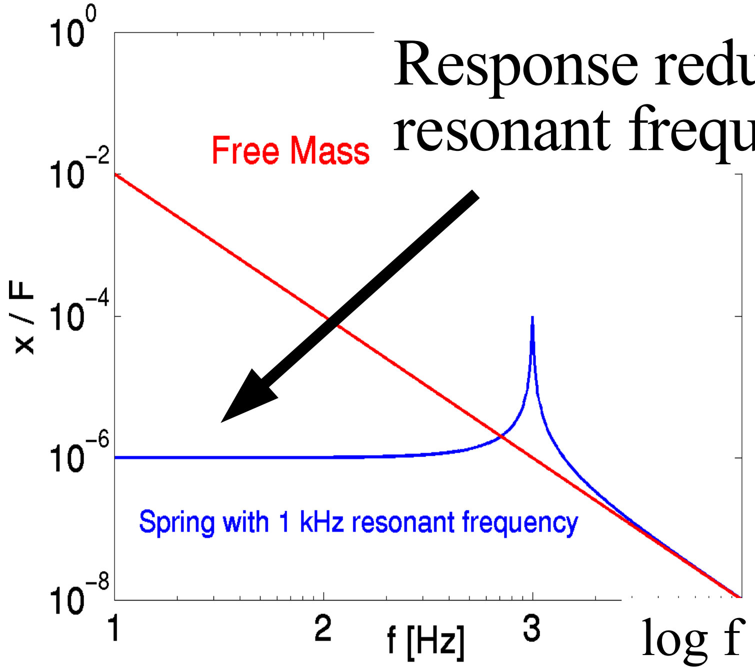
Key ingredients:

- Low mass, low noise mechanical oscillator mirror – 1 g with 1 Hz resonant frequency
- High circulating power – 10 kW
- High finesse cavities - 8000
- Differential measurement – common-mode rejection to cancel classical noise
- Optical spring – noise suppression and frequency independent squeezing



Too much noise -- Optical Springs

- Measuring radiation pressure induced squeezing is hard because it requires an extraordinarily high sensitivity.
- The sensitivity requirement can be relaxed by using an oscillator (with some stiffness) instead of a free test mass.
- Stiff mechanical springs are horrible because they introduce large thermal noise.
- Optical springs do not create thermal noise! They are ideal for this purpose.

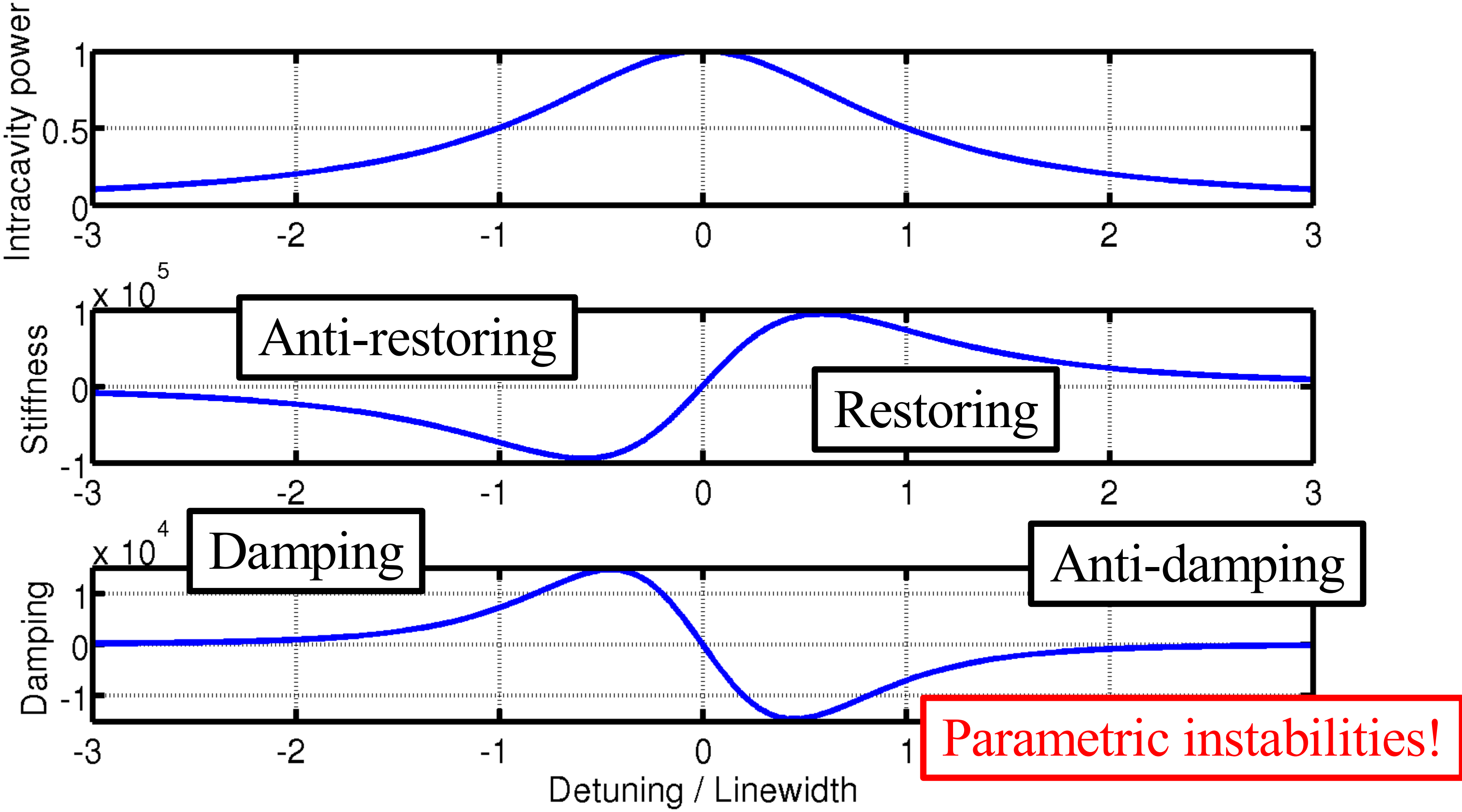


Response reduced below resonant frequency

How to make an optical spring?

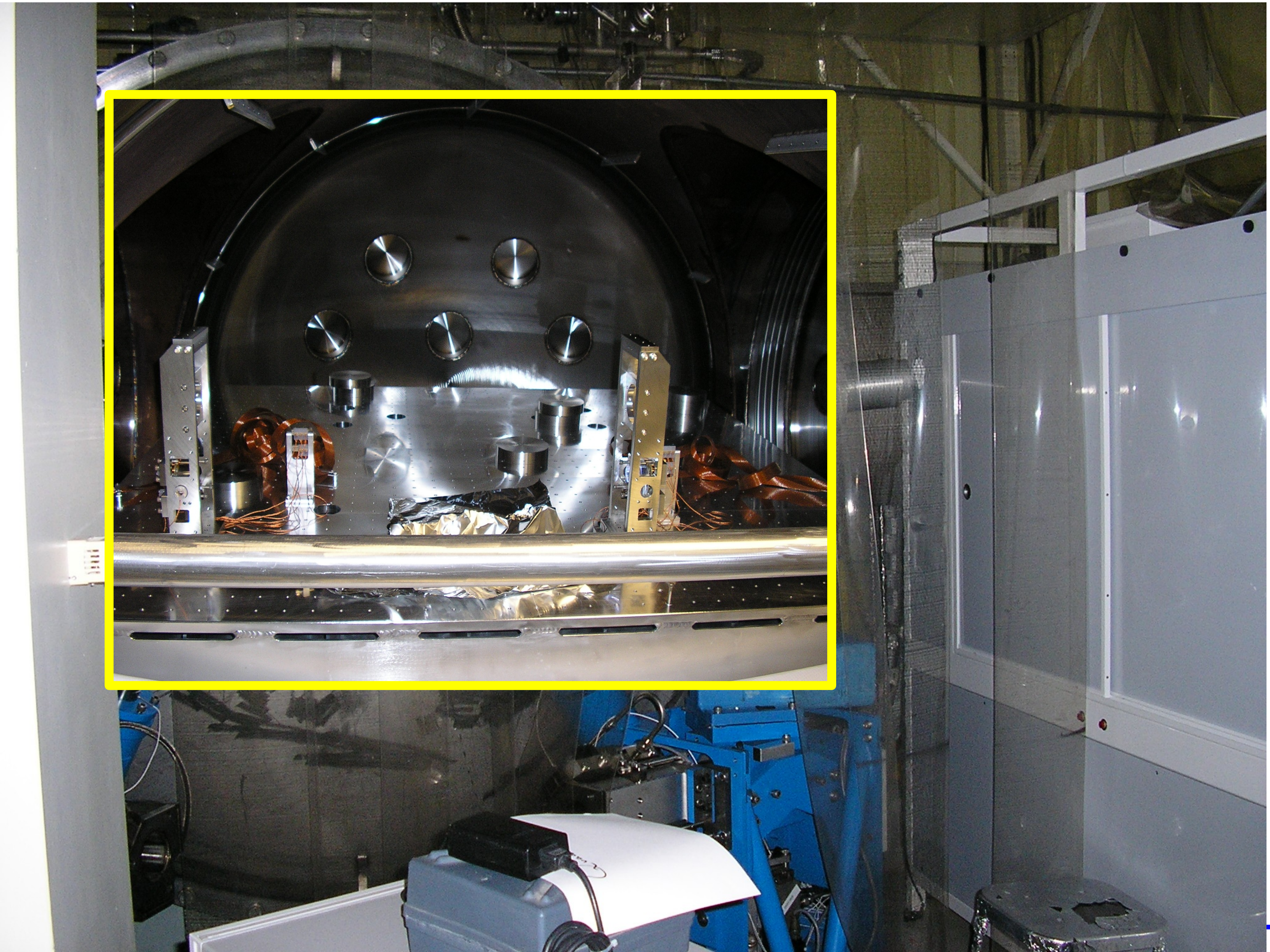
For a detuned cavity, the radiation pressure force is linearly dependent on the length of the cavity, giving a force proportional to the position of the mirror, analogous to a spring constant.

Due to the finite response time of the cavity, a force proportional to the velocity, a viscous damping force, is also formed. This makes the optical spring unstable and also creates parametric instabilities.

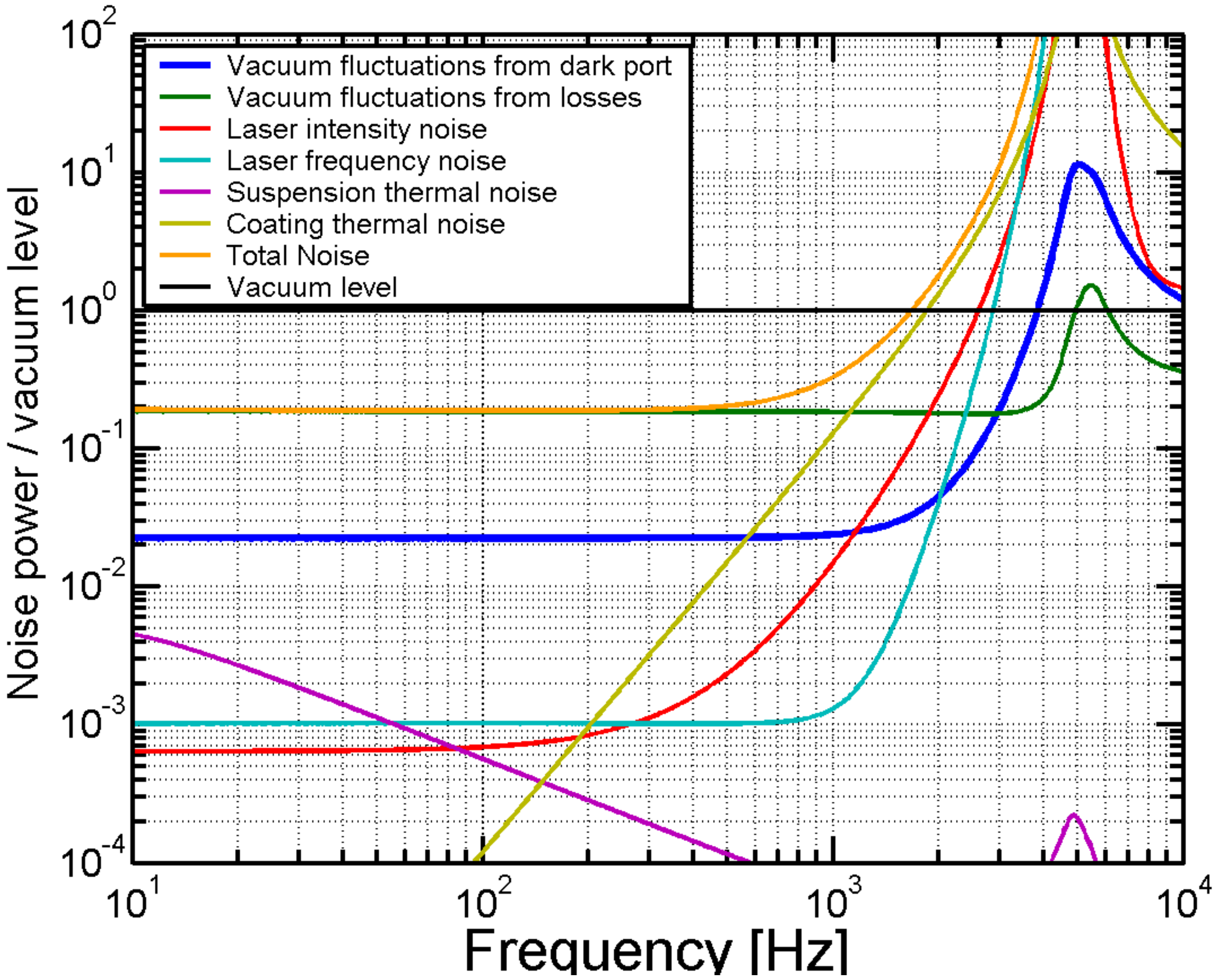


Parametric instabilities!

Platform - LASTI

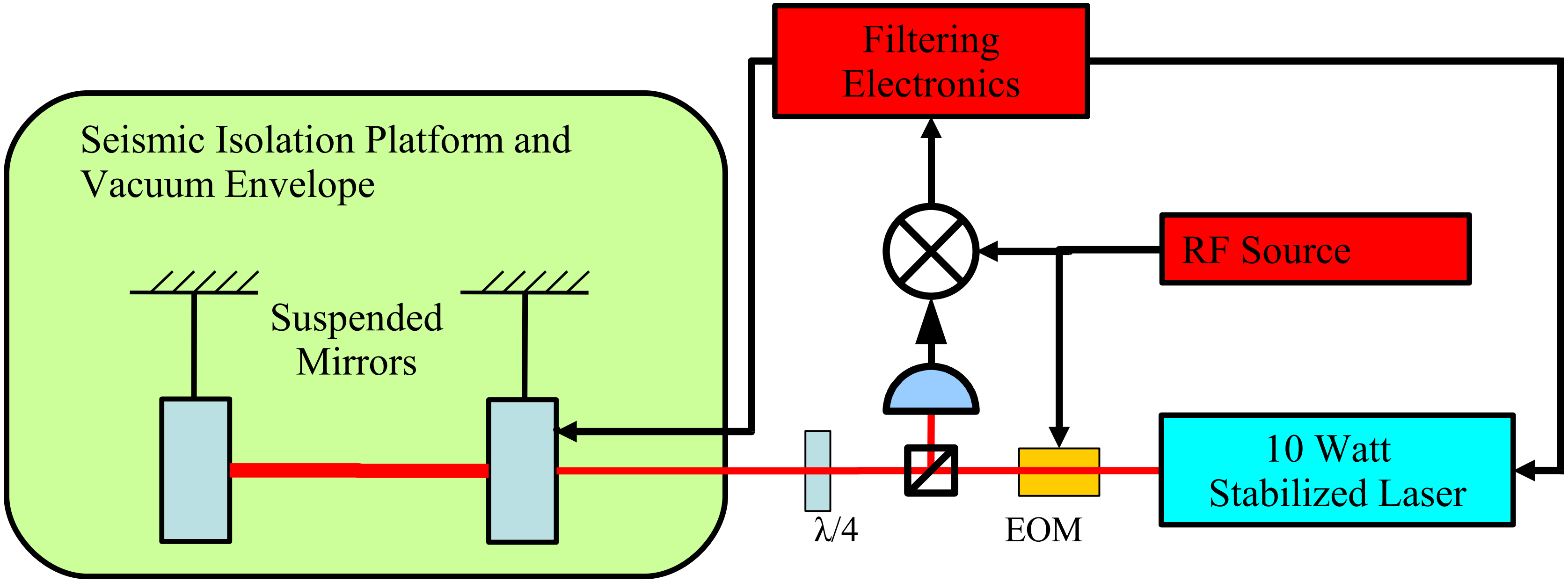


Noise budget



Phase I Experiment

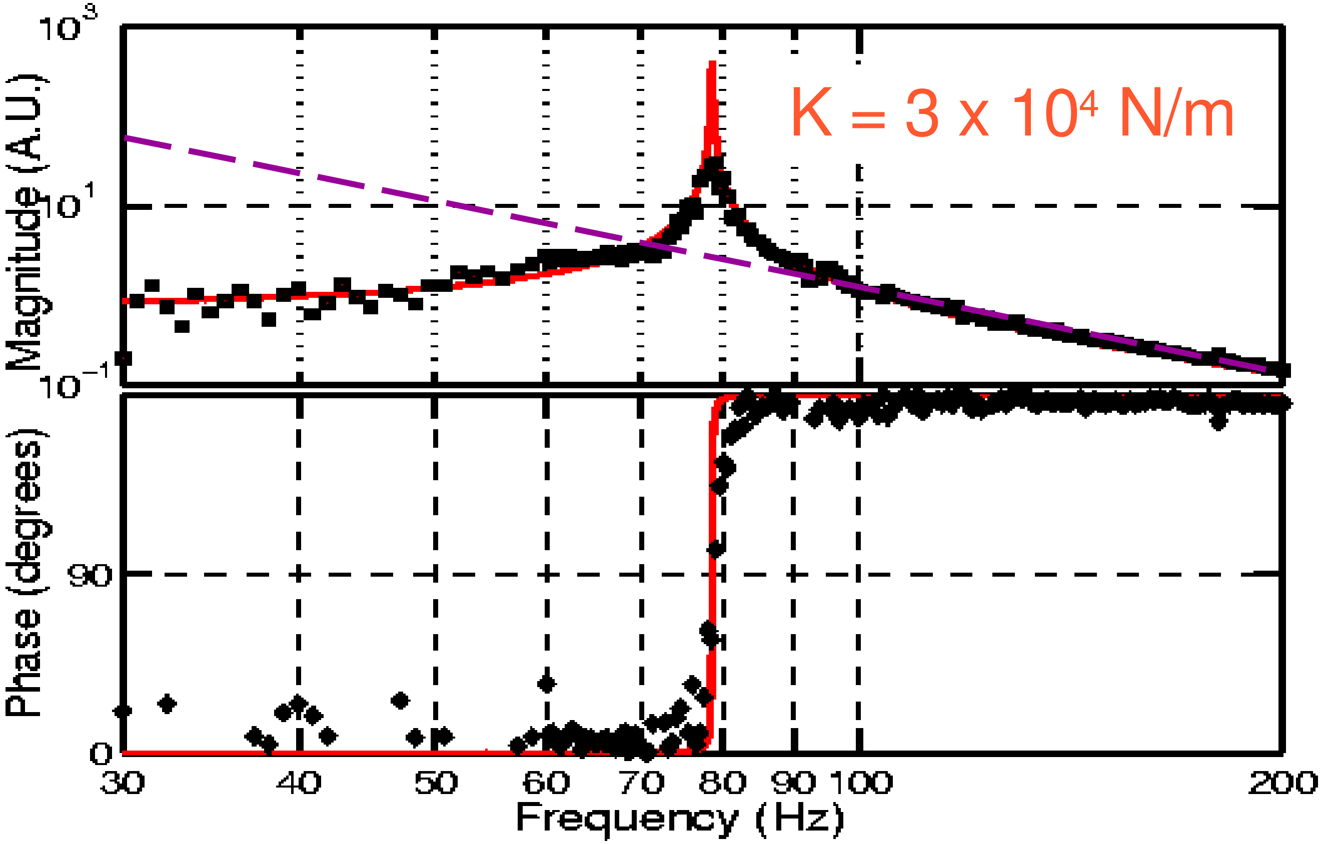
250 gram mirrors, finesse is 1000.



Detuned by inserting offset into PDH error signal, limited to detunings ~ half linewidth.

Optical Spring Measured

- Phase increases by 180°, so resonance is unstable.
- But there is a lot of gain in our servo at this frequency, so it doesn't destabilize the system.
- Stiffness is approximately the same as if the two mirrors were connected by a wood beam with same dimensions as the optical field.



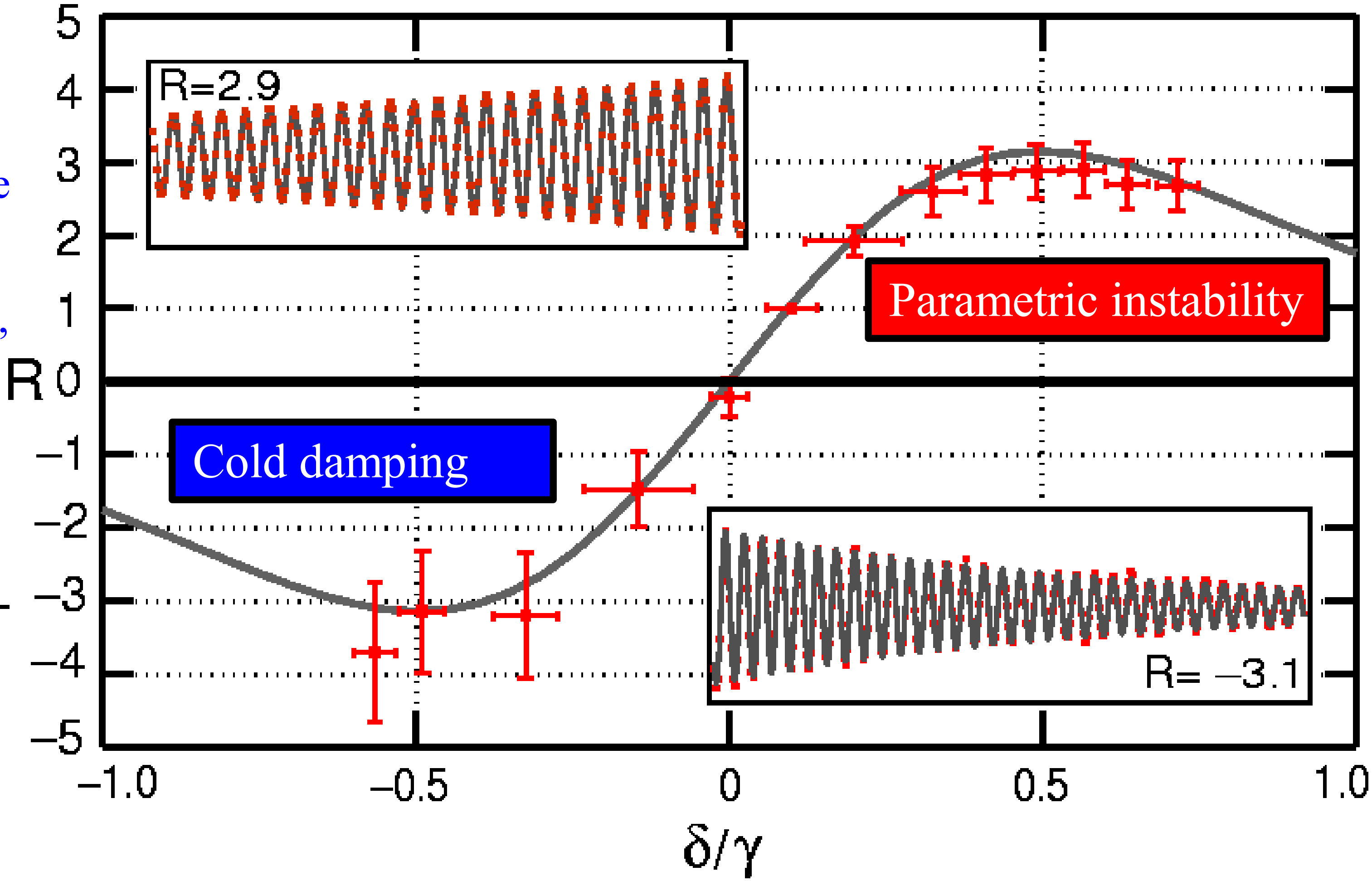
Parametric instability observed and damped!

Acoustic drumhead mode of one mirror became unstable when detuned at high power. The viscous radiation pressure force drives the mode to become unstable – PI! Also when detuned to opposite direction, the Q of the mode is decreased – cold damping!

The mode was stabilized through feedback to the frequency of the laser.

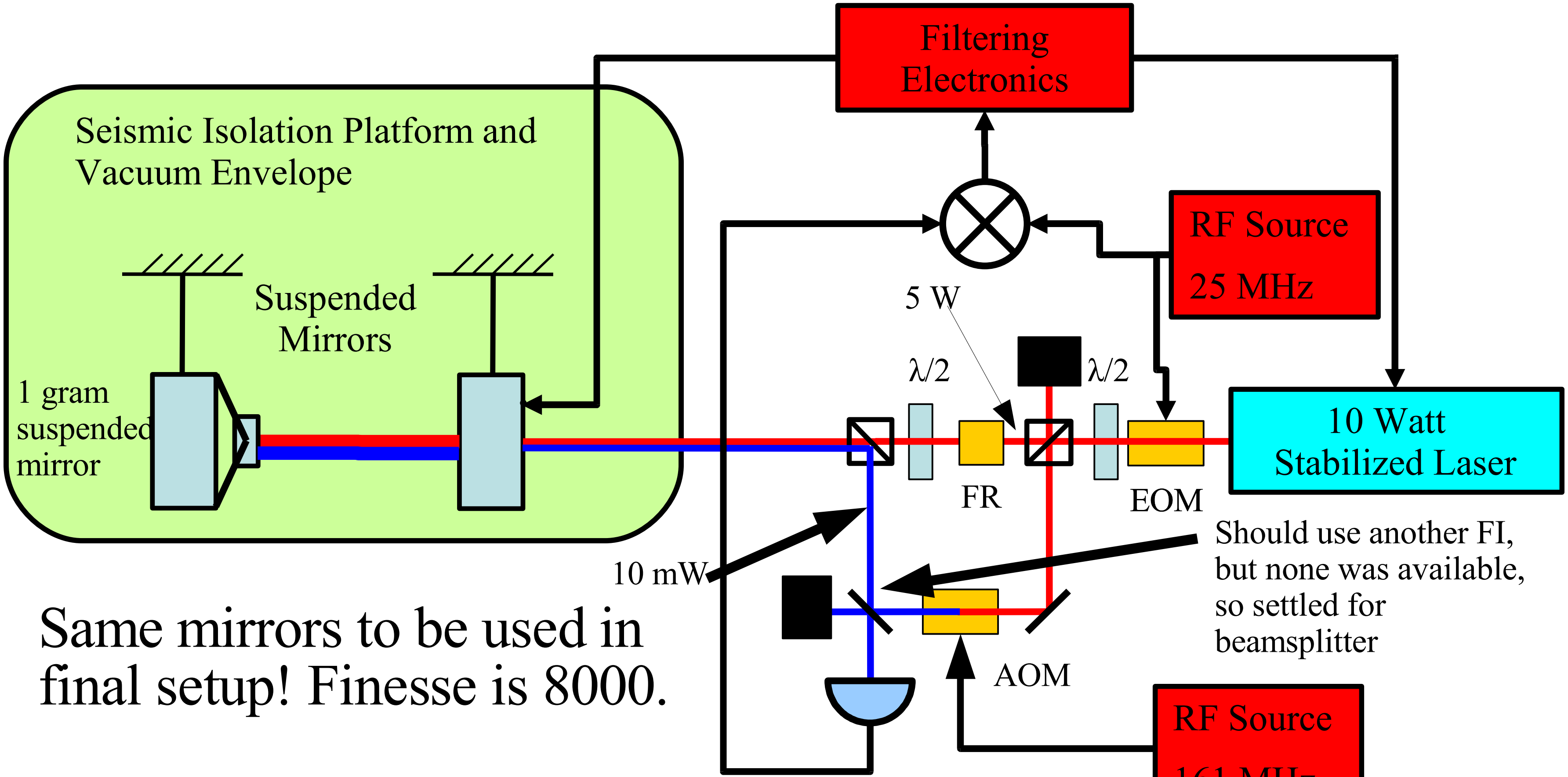
If not stabilized, the mode rings up until cavity loses lock.

$$\tau_{eff} = \frac{\tau}{1-R}$$



Phase II Experiment

10 times higher finesse, 100 times smaller mass, same power as in Phase I! New locking scheme allows for more flexibility: see next slide.

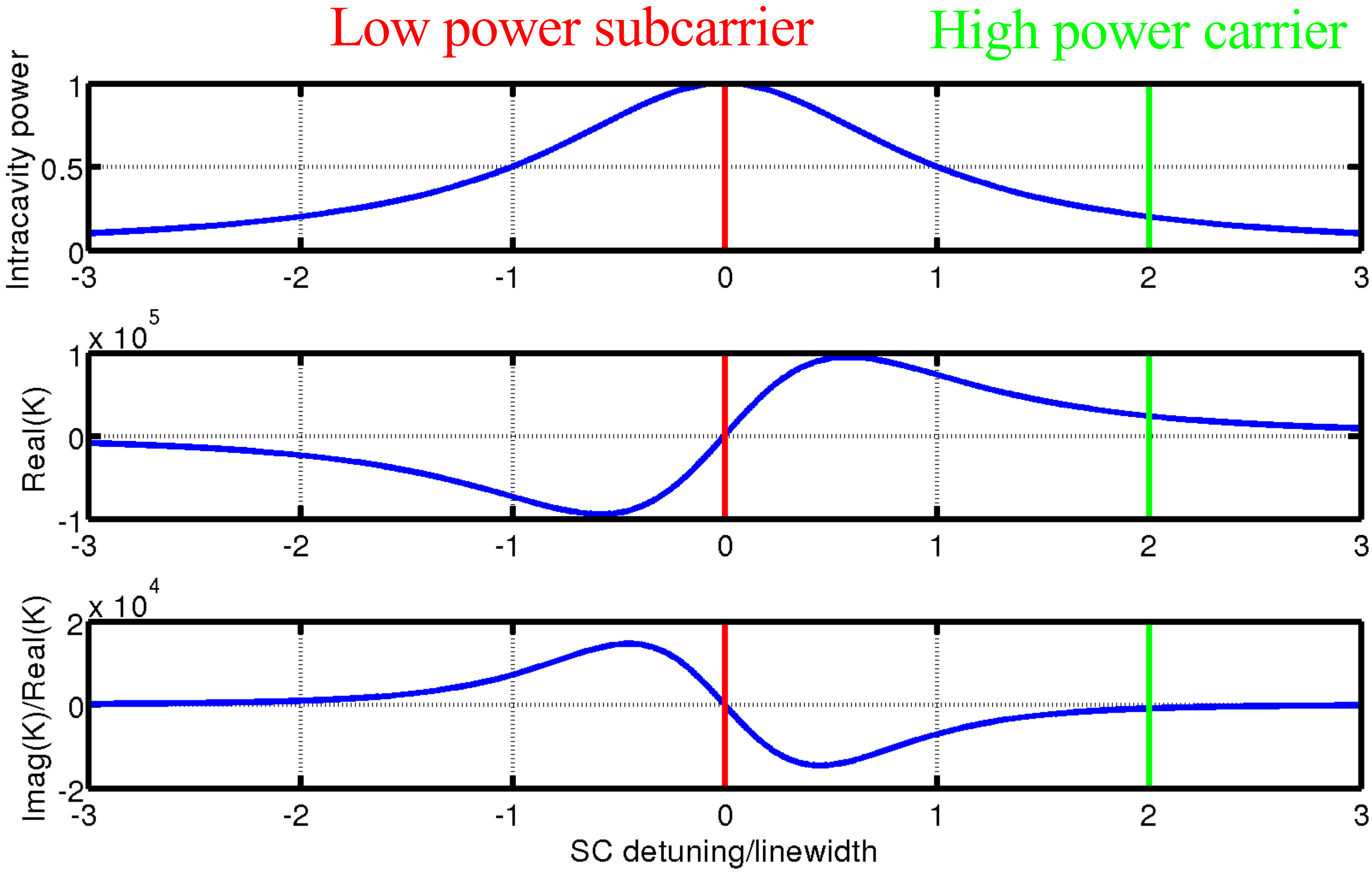


Should use another FI, but none was available, so settled for beamsplitter

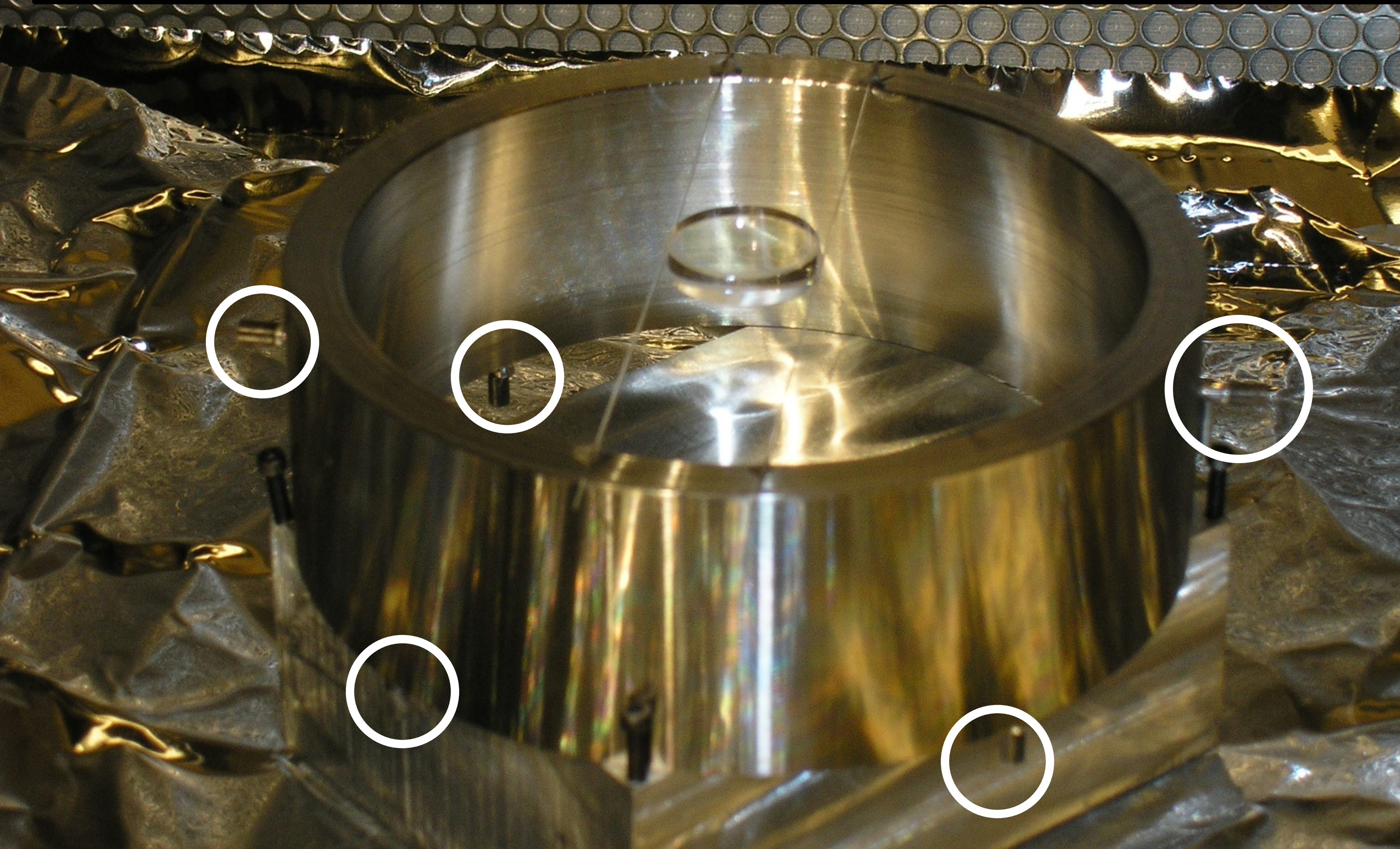
Same mirrors to be used in final setup! Finesse is 8000.

New locking scheme

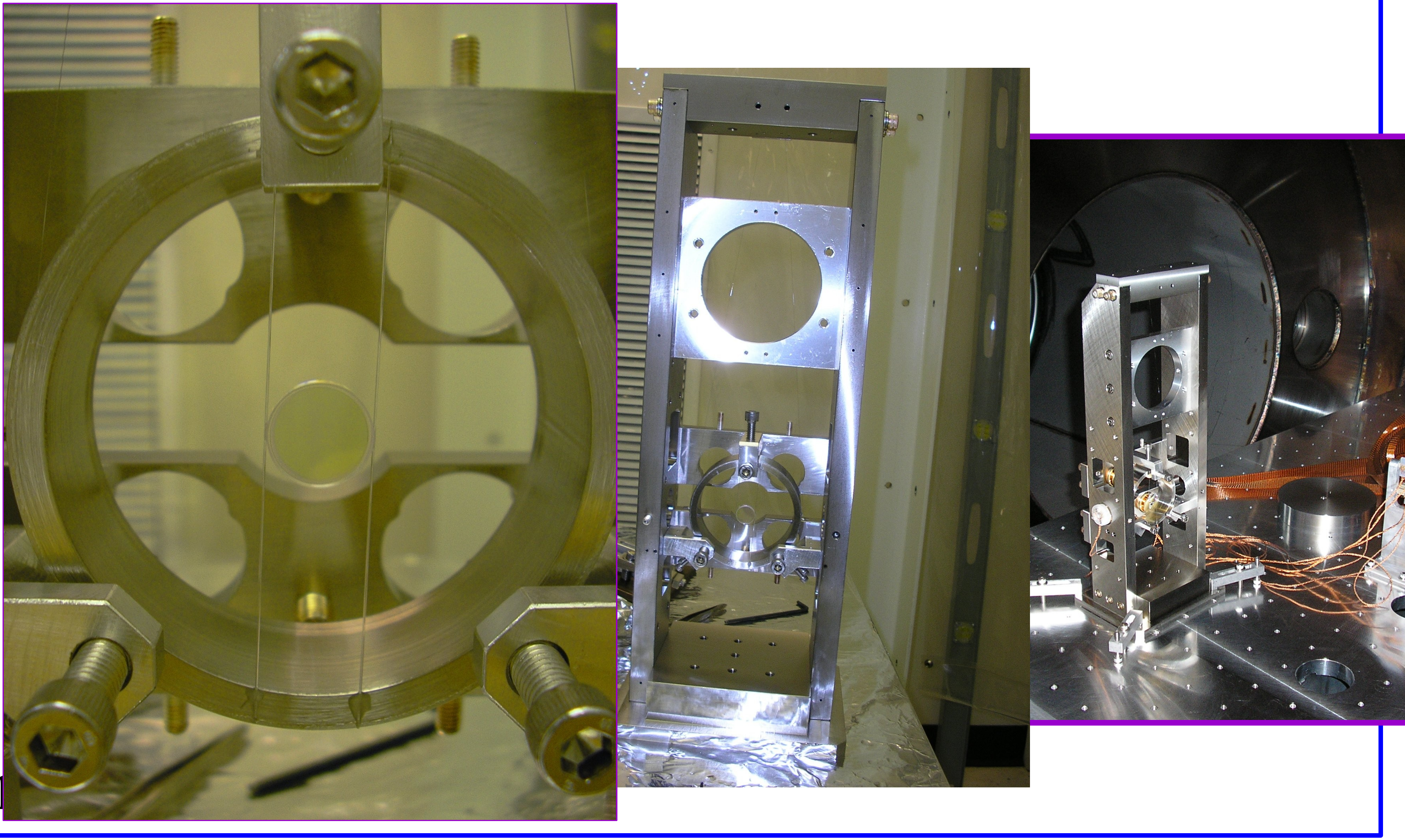
Frequency shift between subcarrier and carrier determines detuning. Any detuning possible!



Steel shell with same diameter as small optics. Suspended as a small optic with magnets, standoffs, etc. Little mirror attached by two 300 micron fused silica fibers. All glued together.



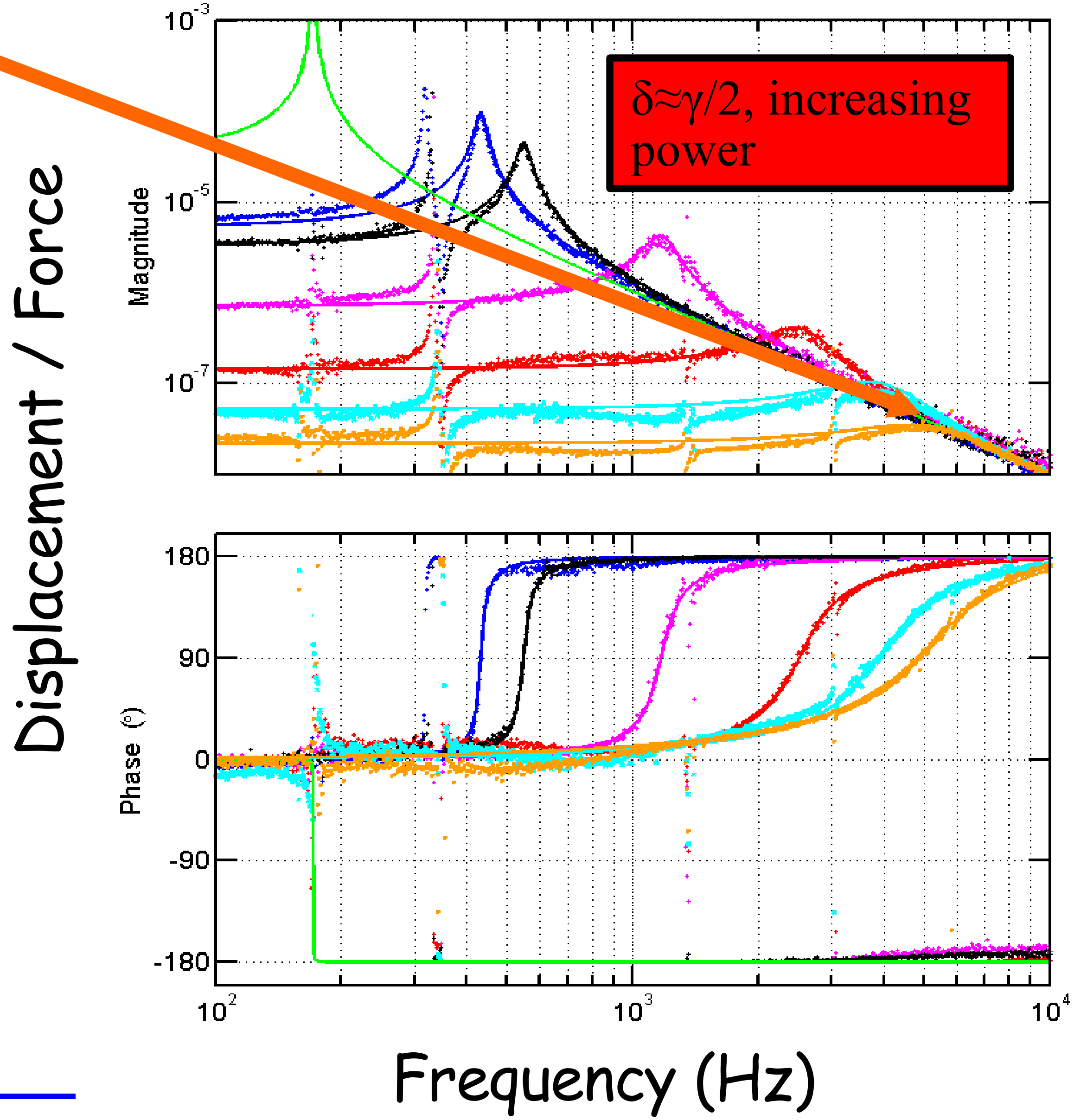
Double suspension for mini mirror



Noise suppression – response of cavity to external disturbance

5 kHz ➔K = 2 x 10^6 N/m (at DC)
Cavity optical mode - stiffest known material?

Twice as stiff as one would expect from a normal 5 kHz spring, due to the frequency being close to the cavity pole.



How stiff is it...?

- Typical person weighs ~ 100 kg, so gravitational force is about ~ 1,000 N. Expected displacement for this force and stiffness is x = F / k = 0.5 mm.
- Very stiff, but also very easy to break. Maximum force it can withstand is only ~ 100 μN, or about 1% of the gravitational force on the little mirror.
- If one replaced the optical mode with a cylindrical beam with same radius (0.7mm) and length (0.92 m), it would need a Young's modulus of:
  - Cavity mode: ***1.2 TPa***
  - Compare to:
    - Steel: ~0.16 Tpa
    - Diamond: ~1 TPa
    - Single walled carbon nanotube: ~1 TPa (fuzzy)

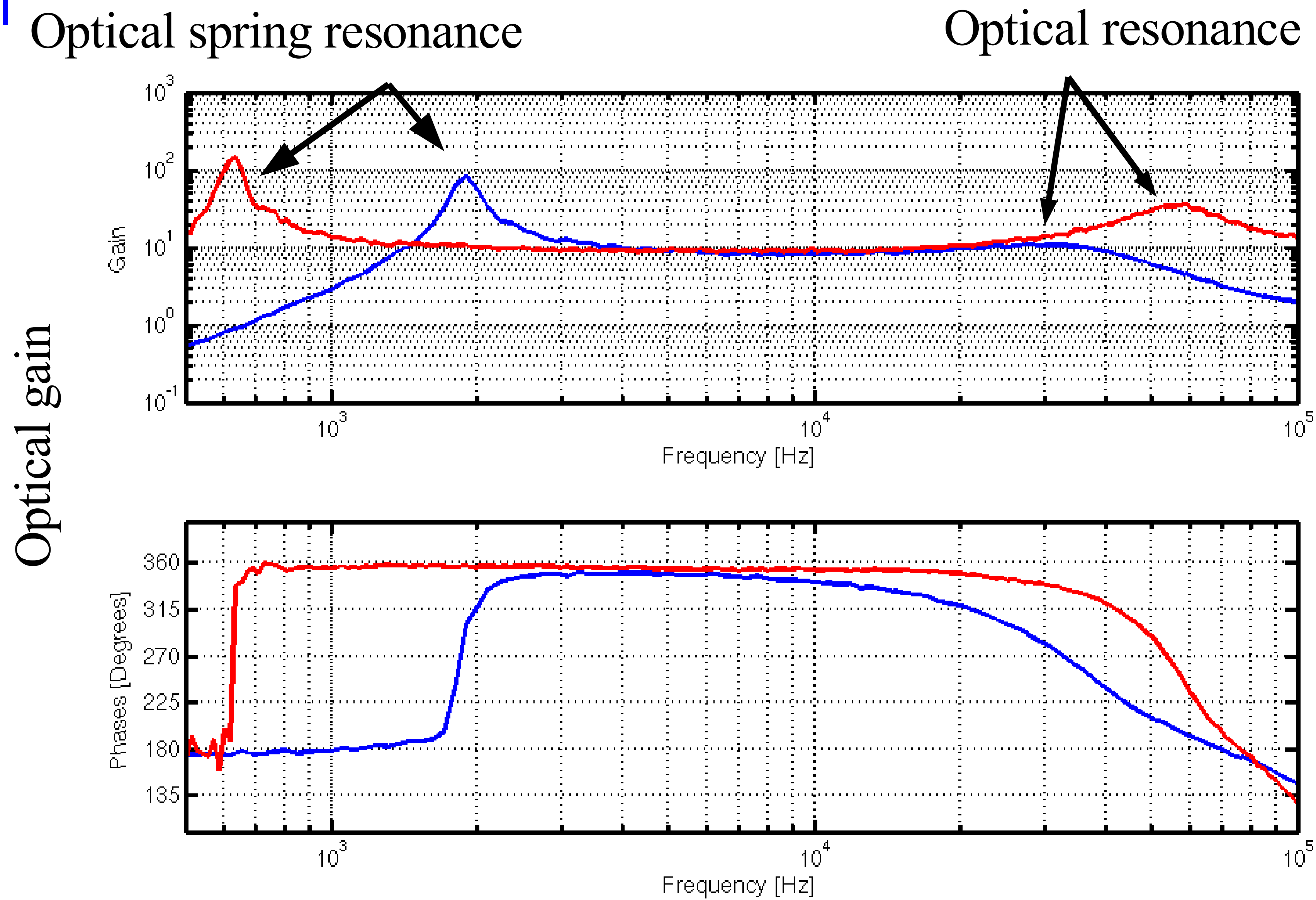
Scale comparison

	Phase II	LIGO	Adv. LIGO	40m
Reduced Mass	1 gram	2.5 kg	10 kg	0.06 kg
Power	20 kW	10kW	1MW	~1 kW?
P/M	**20 MW/kg**	**4 kW/kg**	**100 kW/kg**	**16 kW/kg**
Length scale	0.1 nm	10 nm	0.6 nm	0.6 nm
P/M/L	1(normalized)	10^{-6}	10^{-3}	10^{-4}

Power per mass per length gives a scaling for the magnitude of the dynamics of the radiation pressure effects. This experiment exceeds any other current or planned experiments by several orders of magnitude on this basis. Now just need to make it low noise.

Note:Dynamical length scale is determined by the wavelength divided by the finesse

# Doubly resonant cavity – similar to GEO/Adv. LIGO/40 meter
Detuning = 30,60 kHz, Linewidth = 11 kHz
Only possible with detuning > linewidth.



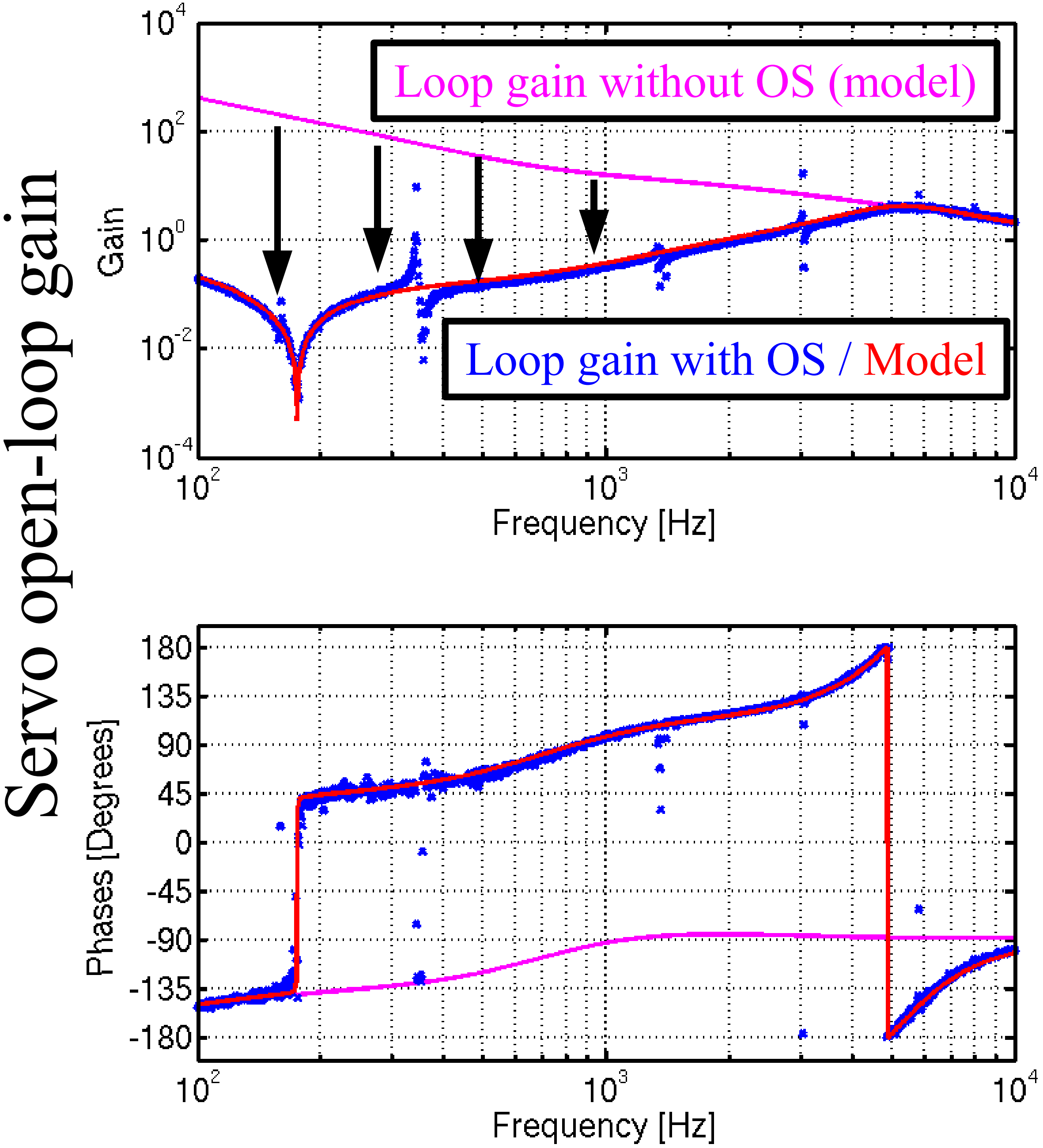
Some interesting numbers

- Max circulating power ~ 25 kW.
- Power density on mirrors ~ 1 MW/cm^2.
- Constant radiation pressure force / gravitational force on little mirror is about 1%.
  - Higher finesse, smaller mirrors and more power... levitated mirrors?
- Undamped PI ringup time constant is ~ 0.5 second, about 10 times more extreme than in Phase I, with R ~ 30.
  - PI is damped through feedback to coils in narrowband loop. Seems to be more robust than feeding back to laser frequency.
- We routinely operate at power levels that exceed the requirements for our ponderomotive squeezer. If we didn't have so much noise (laser and thermal), we could see squeezing now. Laser noise requires the IFO, thermal noise requires the new suspension.

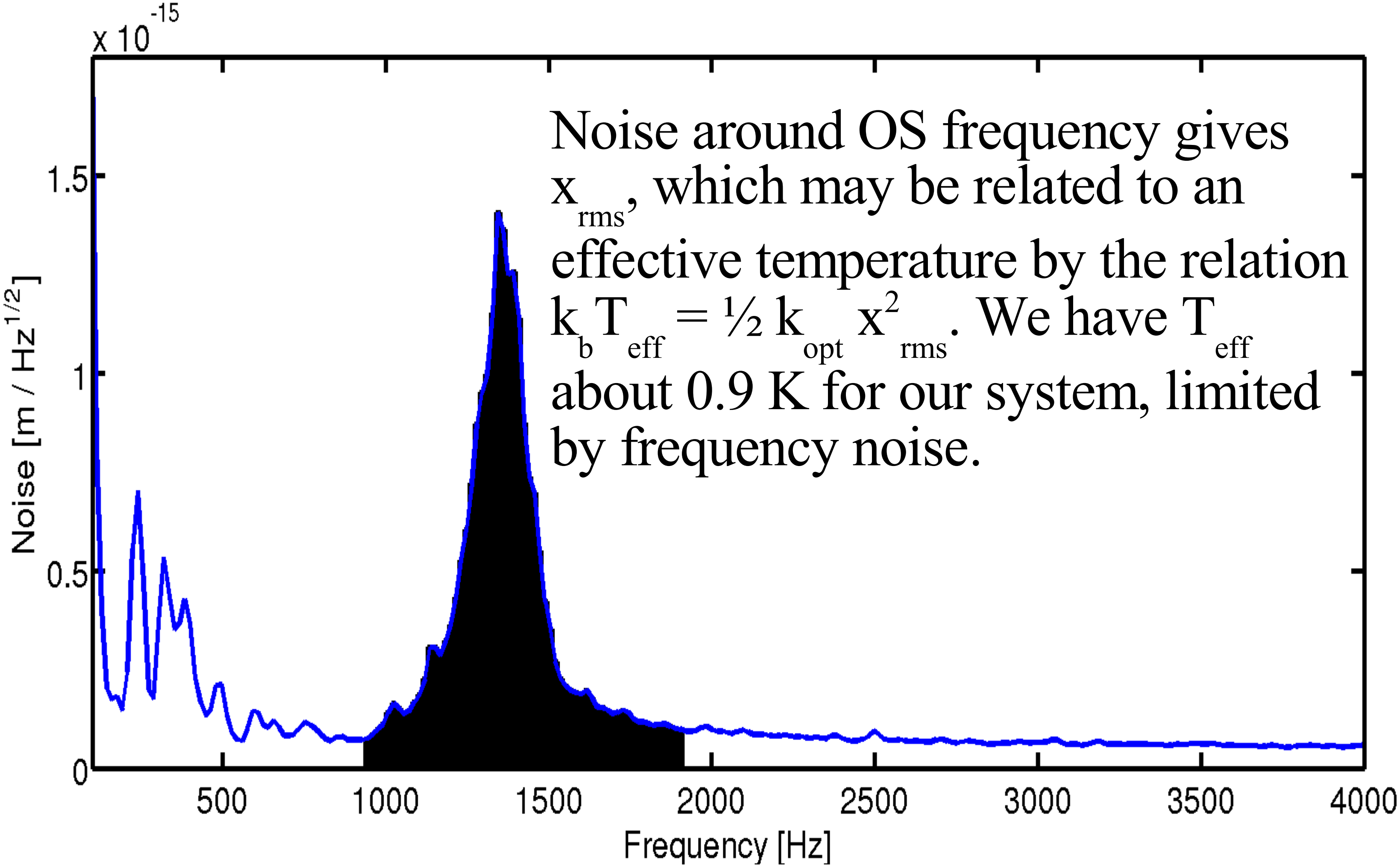
Control

Optical rigidity makes cavity rigid to both force and frequency fluctuations. This can wreak havok on your control system! Our servo is overwhelmed by the optical stiffness.

But this is actually a good thing, since the cavity becomes more stable, and the servo won't interfere with the dynamics – which is essential for ponderomotive squeezing.



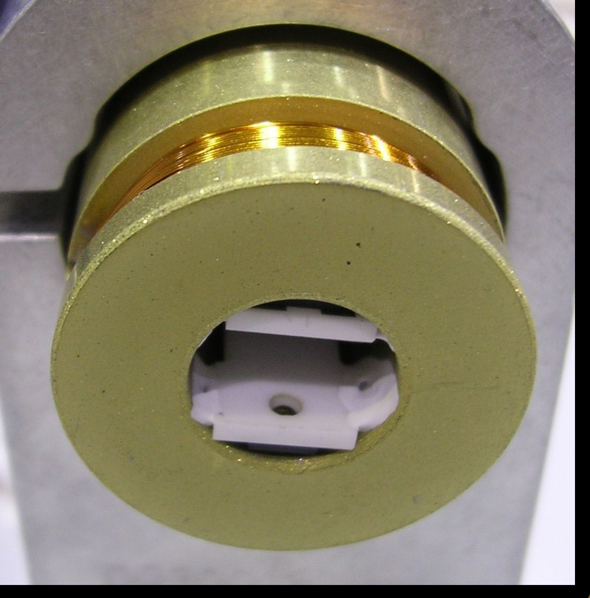
Noise of OS – no extra thermal noise!



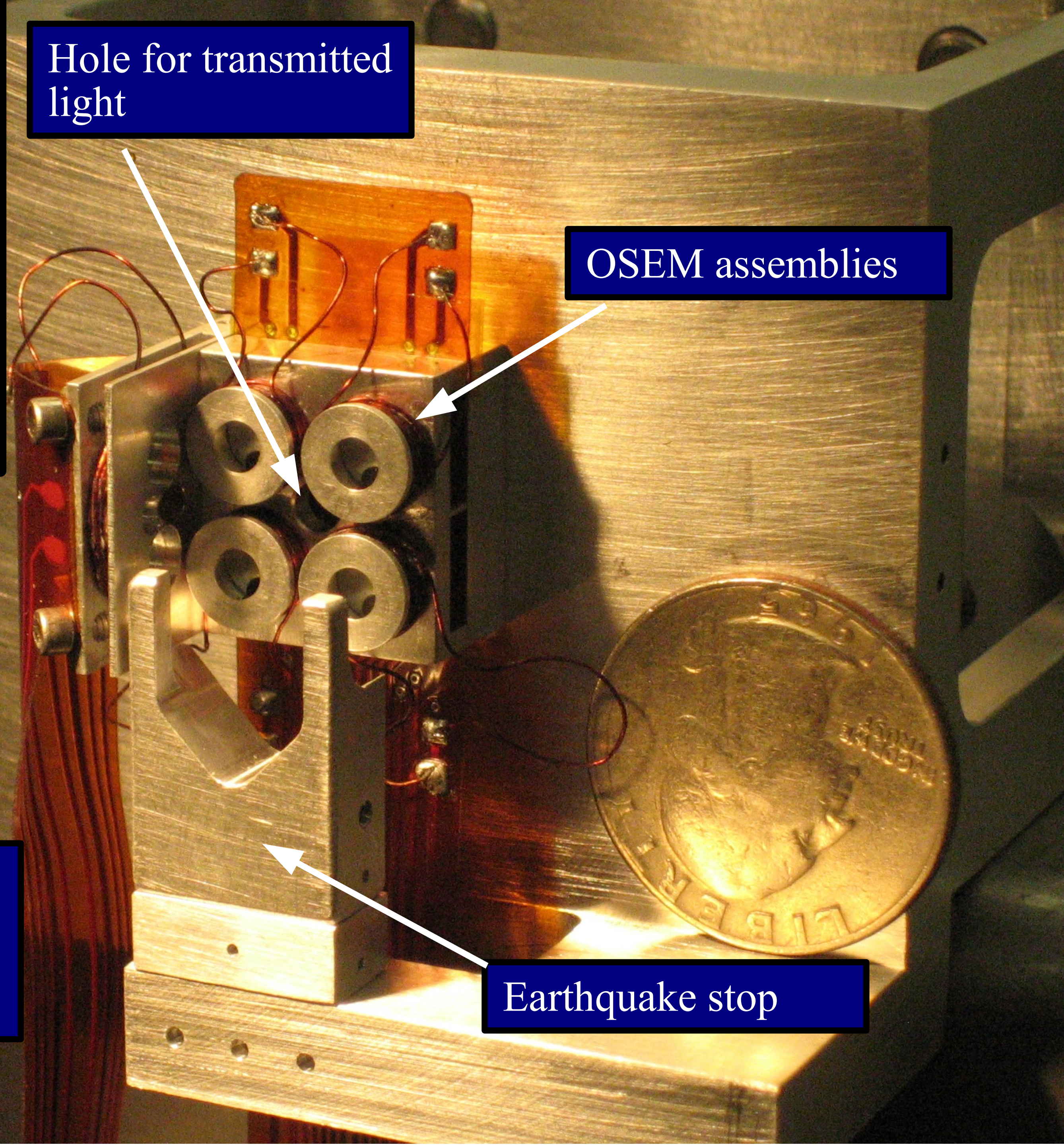
Noise around OS frequency gives x_{rms}, which may be related to an effective temperature by the relation $k_b T_{eff} = \frac{1}{2} k_{opt} x^2_{rms}$. We have T_{eff} about 0.9 K for our system, limited by frequency noise.

What's next?

- Buildup to full IFO
  - Suspension of mini-optic is extremely difficult, but possible, and will happen.
  - Biggest remaining challenge to reach ponderomotive squeezing will be noise reduction: thermal and laser biggest obstacles.



Single LIGO OSEM (roughly to scale)

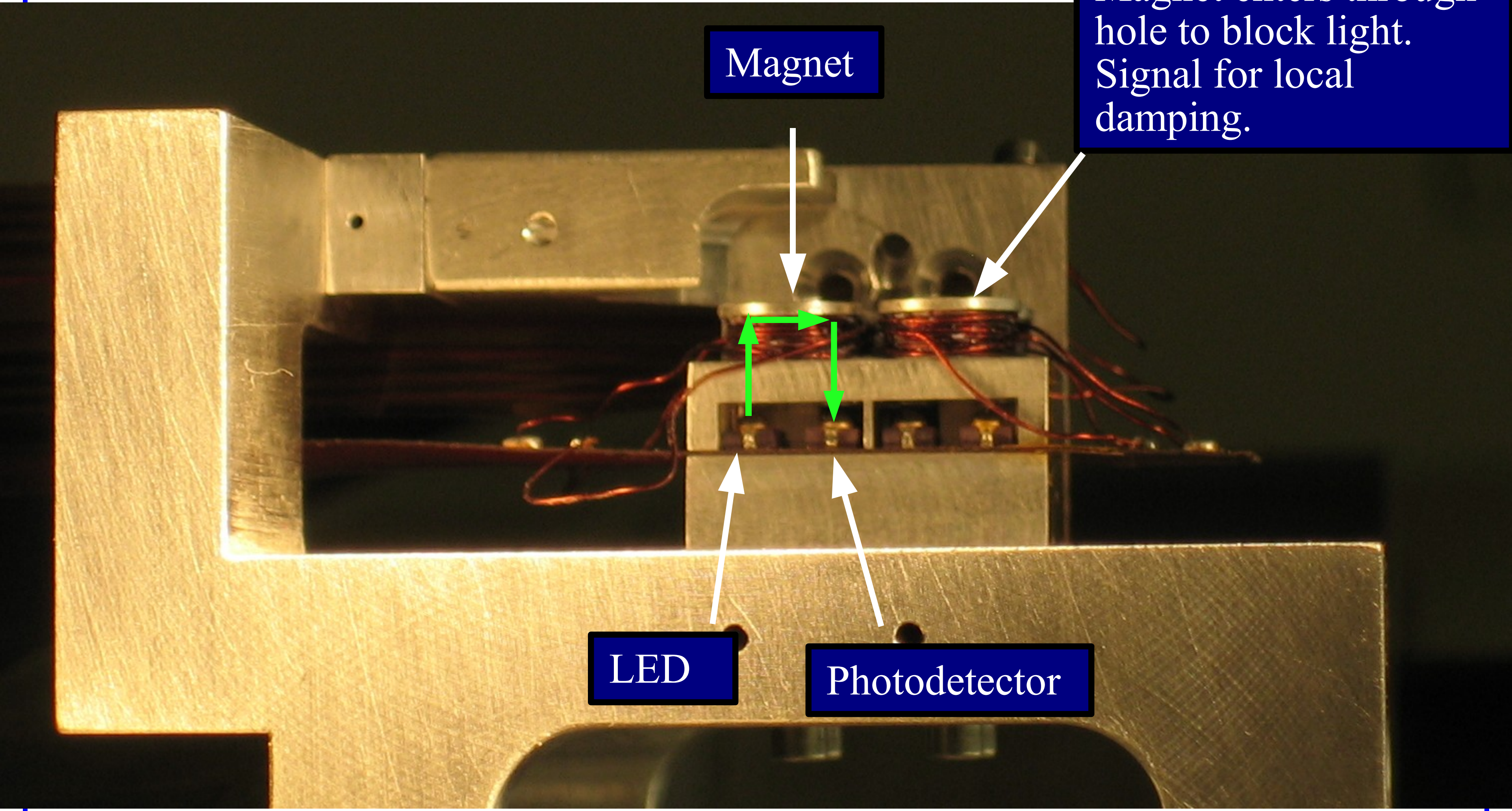


Hole for transmitted light

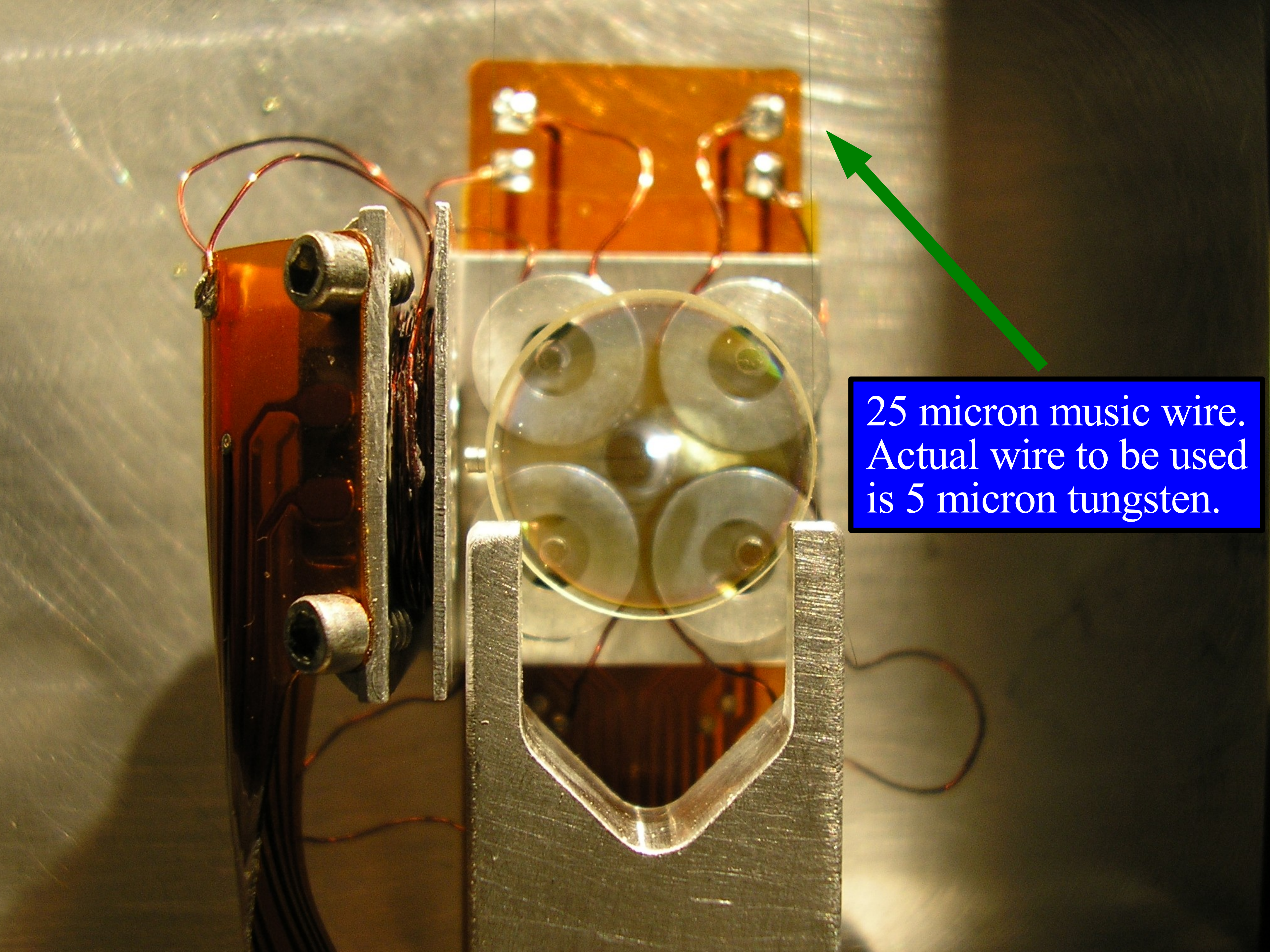
OSEM assemblies

Earthquake stop

5 OSEMs in less space than a single LIGO OSEM



Inside surface of structure is conical and polished to reflect the light from the LED. Magnet enters through hole to block light. Signal for local damping.



25 micron music wire. Actual wire to be used is 5 micron tungsten.

Conclusions

- Radiation pressure effects observed and characterized
  - Optical spring
  - Parametric instability
- Techniques for future experiments explored
  - Damping of extremely unstable OS
  - Control system interaction with OS and PI
  - Locking detuned cavities
  - Testing extremely high power (densities) on small mirrors
    - Nothing has blown up or melted (yet).
  - Operating a system that behaves as the ponderomotive squeezer will behave, at a higher noise level.